

Mapping the stellar populations of the Milky Way with Gaia

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Abstract Gaia will be ESA's milestone astrometric mission, and is due for launch at the end of 2013. Gaia will repeatedly map the whole sky measuring about one billion sources to $V=20$ -22 mag. Its data products will be μ as accuracy astrometry, optical spectrophotometry and medium resolution spectroscopy. A description of the Gaia space mission and its characteristics and performance is given. The expected impact on Galactic stellar population studies is discussed, with particular attention to the sources of interest for CoRoT and *Kepler*.

1 Gaia

Gaia is a major ESA mission with astrometric, photometric and spectroscopic capabilities. It is currently scheduled for launch in December 2013 from Kourou, to be placed at the Lagrangian point L2, 1.5 million km from the Earth in the direction opposite the Sun, for a planned lifetime of 5 years.¹

Gaia represents the natural continuation and a huge improvement with respect to the Hipparcos mission: it will extend the V magnitude limit from 12 to about 20-22 (for blue and red objects respectively), observe a factor 10^4 more sources (including objects such as galaxies and quasars unobservable by Hipparcos), reach a factor ~ 100 better astrometric accuracy, and provide spectrophotometric information for all of the observed objects, as well as spectroscopy for a large fraction of them.

These characteristics are summarized in Table 1, and are described in some more detail in the following.

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¹ For a detailed description of the satellite and system, payload and telescope, functioning and operations see <http://www.rssd.esa.int/index.php?project=gaiaInformationSheets>.

Table 1 From Hipparcos to Gaia.

	Hipparcos ^a	Gaia ^b
Magnitude limit	$V_{lim} = 12$	$V_{lim} = 20-22$ (blue-red sources, respectively)
N. of objects	1.2×10^5	$\geq 10^9$ (2.5×10^7 to $V=15$, 2.5×10^8 to $V=18$)
Quasars	none	$\sim 5 \times 10^5$
Galaxies	none	$\sim 10^6-10^7$
Astrom. accuracy	~ 1 mas	$\sim 7-10 \mu\text{as}$ at $V \leq 12$ $10-25 \mu\text{as}$ at $V=15$, $100-300 \mu\text{as}$ at $V=20$
Broad-band phot.	2 (B,V)	3 (to V_{lim}) + 1 (to $V=17$)
Spectrophotometry	none	2 bands (B/R) to V_{lim}
Spectroscopy (CaT)	none	1-15 km/s to $V=16-17$
Obs. programme	pre-selected targets	all-sky complete and unbiased

^a Final Catalogue: Perryman (1997); New Reduction of the Raw Data: van Leeuwen (2007)

^b Expected Final Catalogue: 2020-22

1.1 Satellite, payload, instruments

The satellite spins around its axis, which is oriented 45-deg away from the Sun, with a period of 6 hr, and the spin axis has a precession motion around the solar direction with a period of 63 days. The combination of these two motions results in the scanning law that allows the entire sky to be observed on average 70 times over the 5 yr mission lifetime (see the transit map in Fig. 1).

The payload is a toroidal structure holding two primary $1.45\text{m} \times 0.50\text{m}$ rectangular mirrors (field of view FoV = $1.7\text{-deg} \times 0.6\text{-deg}$) whose lines of sight are separated by an angle of 106.5-deg (Basic Angle, BA). The BA needs to be known with extremely high precision to ensure Gaia's expected astrometric accuracy, and therefore a BA monitoring system is hosted on the payload, as well as all the optical components which allow to superpose the FoVs of the two mirrors and combine them on the focal plane.

The focal plane contains several arrays of $4.5\text{K} \times 2.0\text{K}$ CCDs:

- i)** the sky mapper (SM), 2×7 CCDs for detection and confirmation of source transit;
- ii)** the astrometric field (AF), 9×7 CCDs corresponding to 40×40 arcmin, for astrometric measurements and white light (G-band, 330-1050 nm) photometry;
- iii)** the blue (BP) and red (RP) photometers, 2×7 CCDs for low resolution ($R < 100$) slitless prism spectro-photometry in the ranges 330-680 nm and 640-1050 nm, respectively. From the spectra the G_{BP} and G_{RP} integrated magnitudes are derived.
- iv)** the radial velocity spectrometer (RVS), 3×4 CCDs for slitless spectroscopy at the Ca II triplet (847-870 nm) with $R \sim 11,000$.

Measurements are made in time-delayed-integration mode, reading the CCD at the same speed as the source trails across the focal plane, i.e. 60 arcsec/sec, corresponding to a crossing/reading time of 4.4 sec per CCD.

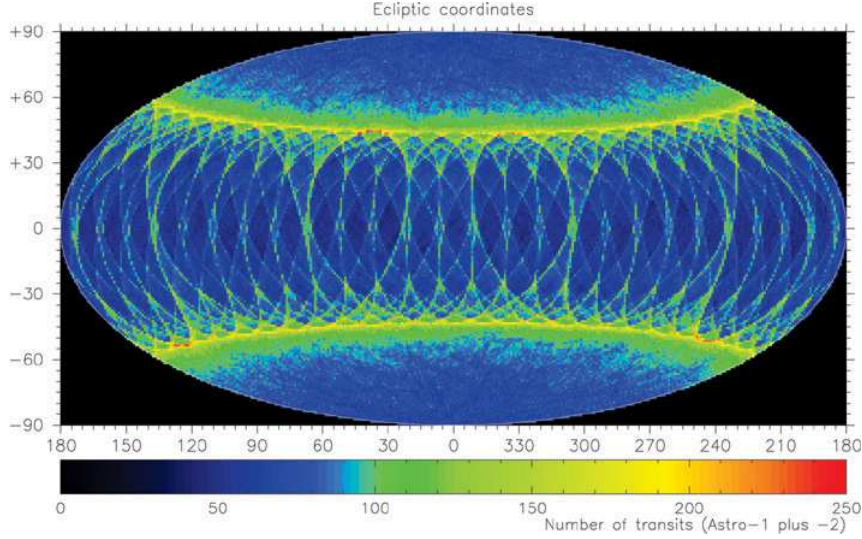


Fig. 1 Dependence of the end-of-mission number of focal plane transits on position on the sky. Shown is an all-sky equal-area Hammer projection in ecliptic coordinates. The maximum number of transits will occur in a ~ 10 -deg wide strip around ecliptic latitudes ± 45 deg.

1.2 Astrometry: measuring principles

The mission is designed to perform global (wide field) astrometry as opposed to local (narrow field) astrometry. In local astrometry, the star positions can only be measured with respect to neighbouring stars in the same field. Even with a very accurate instrument the propagation of errors is prohibitive when making a sky survey. The principle of global astrometry is to link stars with large angular distances in a network where each star is connected to a large number of other stars in every direction.

Global astrometry requires the simultaneous observation of two fields of view in which the star positions are measured and compared. This is provided by the two lines of sight of the primary mirrors. Then, like with Hipparcos, the two images are combined, slightly spaced, on a unique focal plane assembly. Objects are matched in successive scans, attitude and calibration parameters are updated, and object positions are solved and fed back into the system. This procedure is iterated as more scans are added. In this way the system is self-calibrating by the use of isolated non variable point sources, which will form a sufficiently large body of reference objects for most calibration purposes, including the optical definition of the International Celestial Reference System (ICRS) by observing about half a million QSOs.

Therefore Gaia's astrometry will be not only unprecedentedly accurate as far as internal rms errors are concerned, because derived from an all-sky solution, but also unprecedentedly precise in *absolute* values, because obtained with *direct reference to the ICRS*.

1.3 Expected performance

Astrometry Astrometric errors are dominated by photon statistics. Sources at $V \sim 6$ mag represent the bright magnitude limit for Gaia observations, as saturation sets in at that level. The predicted sky-averaged end-of-mission standard errors on the parallax are summarized in Table 2². We note that the standard errors on position and proper motion are about 0.74 and 0.53 of those on parallax, respectively.

Photometry Gaia's photometric data include the integrated white light (G-band) from the AF, and the BP/RP prism spectra from which the G_{BP} and G_{RP} integrated magnitudes are derived. The expected end-of-mission errors are shown in Table 2.

From the BP/RP spectral energy distributions it will be possible to estimate astrophysical parameters using pattern recognition techniques (Bailer-Jones (2010)). For example, one may expect to obtain: i) T_{eff} to $\leq 5\%$ (15%) for a wide range of spectral types brighter (fainter) than $V=16$; ii) $\log g$ to 0.2-0.3 dex (0.2-0.5 dex) for hot ($SpT \leq A$) stars brighter (fainter) than $V=16$; iii) $[Fe/H]$ to ~ 0.2 -0.4 dex (0.5-0.7 dex) down to $[Fe/H]=-2.0$ for cool stars ($SpT > F$) brighter (fainter) than $V=16$; iv) A_V to ~ 0.05 -0.2 mag (0.05-0.3 mag) for hot stars brighter (fainter) than $V=16$.

Ranges in errors reflect the influence of spectral type and metallicity. It is also to be noted that at $V=15$ the degeneracy between T_{eff} and A_V amounts to about 3-4% and 0.1-0.2 mag respectively.

Spectroscopy The RVS provides the third component of the space velocity for red (blue) sources down to about magnitude 17 (16). Radial velocities are the main product of the RVS, with typical end-of-mission errors as shown in Table 2. For sources brighter than ~ 14 mag the RVS spectra will provide information also on rotation and chemistry, and combined with the prism BP/RP spectra will allow us to obtain more detailed and accurate astrophysical parameters.

2 Science with Gaia

“The primary objective of Gaia is the Galaxy: to observe the physical characteristics, kinematics and distribution of stars over a large fraction of its volume, with the goal of achieving a full understanding of the MW dynamics and structure, and consequently its formation and history.” (Concept and Technology Study Report, ESA-SCI-2000-4).

Gaia will provide a complete census of all Galactic stellar populations down to 20th magnitude. Based on the Besançon Galaxy model (Robin et al. 2003, Robin et al. 2004) Gaia is expected to measure more than 10^9 stars belonging to the thin and thick disk, the bulge and the spheroid. Binaries, variable stars and rare (i.e. fast-evolving) stellar types will be well sampled, as well as special objects such as So-

² See <http://www.rssd.esa.int/index.php?project=gaia> Science Performance, April 2011 update.

Table 2 End-of-mission expected standard errors of astrometric, photometric and spectroscopic data as a function of Johnson V magnitude for three unreddened reference spectral types. Left: sky-averaged parallax errors (in units of μas) for B1V, G2V, and M6V. Middle: photometric errors in the $G\text{-}G_{BP}\text{-}G_{RP}$ bands, in units of milli-magnitude, for B1V, G2V, and M6V. Right: radial velocity errors (in units of km/s) for A0V, G5V and K4V.

V (mag)	σ_π (μas)			σ_{phot} (mmag)			σ_{RV} (km/s)		
	B1V	G2V	M6V	B1V	G2V	M6V	A0V	G5V	K4V
6-12	7	7	7	1-4-4	1-4-4	1-4-4	1-2	1	1
13	11	10.5	7.5	1-4-4	1-4-4	1-4-4	3	1	1
15	27	26	10	1-4-5	1-4-4	1-6-4	16	3	2
16	41	41	15	1-4-5	1-5-5	1-9-4		7-8	4
17	70	66	23	2-5-7	2-5-5	2-20-5		20	10
18	110	107	40	2-7-14	2-9-8	2-49-5			
20	340	333	100	3-29-83	3-43-43	3-301-17			

lar System bodies ($\sim 10^5$), extra-solar planets ($\sim 2 \times 10^4$), WDs ($\sim 2 \times 10^5$), BDs ($\sim 5 \times 10^4$).

One billion stars in 5-D (6-D if the radial velocity is available, and up to 9-D if the astrophysical parameters are known as well) will allow us to derive the spatial and dynamical structure of the Milky Way, its formation and chemical history (e.g. by detecting evidence of accretion/merging events), and the star formation history throughout the Galaxy. The huge and accurate database will provide a powerful test-bench for stellar structure and evolution models. The superb astrometric and photometric accuracy will allow us to obtain proper-motion-cleaned Hertzsprung-Russell diagrams throughout the Galaxy, and hence complete characterization and dating of all spectral types and Galactic stellar populations. The dark matter distribution will be mapped by the distribution and rate of microlensing events. The cosmic distance scale will be accurately defined on a reliable ground thanks to the distance (i.e. luminosity) calibration of the primary standard candles, RR Lyraes and Cepheids.

2.1 MW stellar population studies with Gaia: a few examples

The Bulge: $\sim 1.7 \times 10^8$ stars Our knowledge of the Galactic bulge has greatly improved in the last decade(s), and presently the structure of the bar is constrained from modelling of gas dynamics, stellar surface brightness and stellar dynamics. However many questions remain open, for example (just to quote a few) on the formation mechanism (single enrichment event or merging from chemically distinct subcomponents?), on the chemical evolution timescale (less than 1 Gyr or more extended?), on the presence of chemodynamical subpopulations, on the relation with other Galactic populations, especially the inner disk (see Rich 2013 for a review).

Gaia will make a major contribution to the solution of these problems by measuring accurate distances and proper motions of several millions of stars, as well

as a huge number of radial velocities (to $V=17$ mag), especially in bulge fields at $b < -6^\circ$ where the X-shaped structure is important. The northern bulge will also be observable, because red clump stars can be reached by Gaia even with $\sim 3\text{--}4$ mag extinction. Simulations show that, at the reference distance of 8 kpc, a typical tracer such as a red clump star (M0III, $M_V=-1$ mag) dimmed by 4 mag extinction would have $V=17.5$. Gaia will measure its parallax with an rms error of $\sim 50 \mu\text{as}$ and proper motion to ~ 1 km/s, as well as the radial velocity to ≤ 15 km/s, and obtain useful information on its astrophysical parameters (and hence age and chemical properties). Complementary high-dispersion spectroscopy, e.g. by the Gaia-ESO Survey (GES), HERMES and 4MOST, will provide more detailed information on chemistry and kinematics.

The Disk(s) : $\geq 10^9 \text{ stars}$ In recent years several photometry and spectroscopy surveys have greatly increased the number of stars with good distances, radial and transverse velocities, and abundance estimates. However, an enormous amount of practical and conceptual work needs to be done to answer the many questions still open in this field (see Rix & Bovy (2013) for a review).

Based on current simulations, the effective volume that Gaia will explore will be limited to only a quadrant of the Galactic disk, because of dust extinction and image crowding. Assuming as a typical tracer a K3III star ($M_V=0$ mag) dimmed by 2 mag extinction, the disk can be mapped as far as 10 kpc with individual distance errors $\leq 50 \mu\text{as}$, proper motion errors ≤ 1.5 km/s, radial velocity errors ≤ 10 km/s, and with additional information on astrophysical parameters and ages. The huge number and high accuracy of these data will provide a major breakthrough in the understanding of the many aspects related to the disk formation, structure and evolution (see K. Freeman's contribution, this meeting).

The Halo : $\sim 2 \times 10^7 \text{ stars}$ Typical tracers of the field halo population, which have been used in several studies, are red giants (K3III, $M_V=-1$), HB stars (A5III, $M_V=+0.5$), and MS-TO stars (G2V, $M_V=+4.5$). With the former two stellar types Gaia will map the inner halo as far as 10 kpc with proper motion errors $\leq 1 \text{ km s}^{-1}$, and the outer halo as far as 30 kpc with proper motion errors of $\sim 3\text{--}7 \text{ km s}^{-1}$, respectively. The much fainter (but more numerous) MS-TO stars can be used to map the inner halo as far as 4 kpc with proper motion errors $\leq 1 \text{ km s}^{-1}$ (as far as 10 kpc to $6\text{--}7 \text{ km s}^{-1}$). By these in-situ measurements it will be possible to settle questions such as the inner/outer halo dichotomy, their origins and mechanisms of formation (if different) and hence the merger history of the Galaxy, and derive the gravitational potential of the Milky Way's dark matter halo. The synergy with LSST will be especially fruitful to extend these results at fainter magnitudes (see Ivezić et al. 2012 for a review).

3 CoRoT and *Kepler* targets

The study of the dynamical and chemical evolution of stellar populations in the Galaxy requires accurate data on kinematics (velocities), chemical properties (abundances) and ages (distances, astrophysical parameters) for a significant fraction of MW stars. Gaia, in synergy with the large ongoing or forthcoming photometric and spectroscopic surveys, will provide enormous amounts of such data in the next decade. Accurate ages for individual field stars, however, are quite difficult to acquire, and asteroseismology can make a fundamental contribution by estimating ages, e.g. for individual red giants. These stars are bright and allow us to probe the evolution of populations across the whole Galaxy as far as its more distant parts.

During their searching campaigns for exoplanets around late type (mostly F-M) dwarf stars, CoRoT and *Kepler* found thousands of red giants with solar-like oscillations, which could be analyzed with asteroseismology techniques to derive their physical parameters, distances and ages. As an example, we consider the work by Miglio et al. (2013) who analyzed about 2000 red giants with solar-like oscillations in two exofields of the CoRoT survey extending about 8-10 kpc each, on opposite directions with respect to the Sun. The stars are selected to be brighter than $R=16$. For our simulations of Gaia observations we have assumed as templates the spectral types G8III, K3III and M0III. For the sake of completeness, we have performed simulations also for two template red dwarfs, i.e. F6V and G2V, which are targets of the CoRoT and *Kepler* surveys as well.

The characteristics of these stars, and the expected astrometric and kinematic performance of Gaia at the adopted $R_{lim}=16$ are summarized in Table 3³. The Gaia photometric errors at these levels of magnitude are a few mmag (see Table 2). As mentioned in Sect. 1.3, for stars brighter than ~ 16 mag the spectrophotometric data are expected to give good information on stellar astrophysical parameters such as temperature, gravity, metallicity and reddening; somewhat less accurate, but still useful estimates of these parameters can be obtained down to ~ 18 mag.

Table 3 CoRoT red stars with solar-like oscillations: expected end-of-mission errors on parallax, transverse velocity (from proper motions) and radial velocity (from the RVS) from Gaia measures, at the magnitude limit $R_{lim}=16$ assuming zero reddening.

Sp. Type	V-R (mag)	V (mag)	M_V (mag)	Dist - Par (kpc) - (μ as)	σ_π (μ as)	p.m. σ_{TV} (km/s)	RVS σ_{RV} (km/s)
G8III	0.50	16.50	+0.6	15 - 66	40	1.5	11
K3III	0.64	16.60	+0.1	20 - 50	40	2.0	5
M0III	0.88	16.90	-0.4	29 - 35	39	2.9	7
F6V	0.29	16.30	+3.5	3.6 - 275	39	0.3-0.4	15
G2V	0.37	16.40	+4.8	2.1 - 480	39	0.2	12

³ Astrometric simulations are based on de Bruijne (2009), GAIA-CA-TN-ESA-JDB-055.

To complement the information given in Table 3, we plot in Fig. 2 the detailed behaviour of the expected astrometric accuracy (i.e. percent error on parallax) as a function of distance, which shows the range of distances that can be reached by the various spectral types to $\leq 30\%$, for two values of reddening.

The results of these simulations indicate that there is an area of overlap where the combined use of Gaia's data and asteroseismology techniques can be very fruitful. On the one hand, Gaia will provide a complete census and very accurate multi-fold information for the nearest and brightest stars accessible to asteroseismology, and hence facilitate the selection of targets and initial input parameters. On the other hand, the cross-verification of Gaia's results by the very detailed and independent asteroseismology techniques, even if applicable only to a small subsample of stars, will help understand in finer detail Gaia's results and calibrate them on physical grounds. Possible discrepancies, if any, only promise to open the path to deeper understanding.

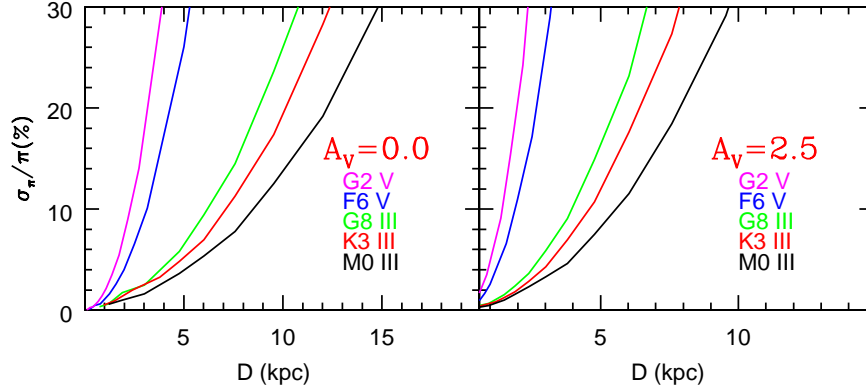


Fig. 2 The lines show Gaia's expected accuracy on parallax measures as a function of distance, for the same spectral types listed in Table 3.

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